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The HEC RAS model of regulated stream for purposes of flood risk reduction

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Abstract

The work highlights the modeling of water flow in open channels using 1D mathematical model HEC-RAS in the area of interest Lopuchov village in eastern Slovakia. We created a digital model from a geodetic survey, which was used to show the area of inundation in ArcGIS software. We point out the modeling methodology with emphasis to collection of the data and their relevance for determination of boundary conditions in 3D model of the study area in GIS platform. The BIM objects can be exported to the defined model of the area. The obtained results were used for simulation of flooding. The results give to us clearly and distinctly defined areas of inundation, which we used in the processing of Cost benefit analysis. We used the developed model for stating the potential damages in flood vulnerable areas.

Key words: HEC-RAS, mathematical modeling, BIM technologies, GIS

1 Introduction

In the nineties of the twentieth century, especially in the field of mechanical engineering the tools of mathematical modeling have been started to use for purposes of analyzing the engineering designs for planning of production and for modeling and simulations of production management. At present, these procedures are mainly used to improve the process of shortening the pre-production phase necessary for the introduction of production. In civil engineering this knowledge is used for creating the projects more efficient in terms of work proceeding, excluding the amount of errors, described by linking the text and image information that represent the elements of the real world (BIM, GIS).

BIM (Building Information Modeling) is integrated model aimed to provide coordinated and reliable information about the project of the construction during the separate phases of the project from design through its implementation to the operation. BIM offers to engineers, constructors and investors possibility to make better decisions, improve the quality and increase the profitability of the construction with maximum using of infrastructure. It supports the continuous and immediate availability of the project during its implementation, time schedule and cost information that are reliable, integrated and coordinated [1].

The BIM process utilizes an intelligent object of centralized architecture in high detail 3D display, while in the GIS is used basic 2D representations of these entities (points, lines, polygons) and it creates space in relation to the surrounding country [2]. It is therefore an organizing information system (Figure 1) which acquires proceeds, adjusts, analyzes and displays all forms of geographical information.

Figure 1: Design and development of BIM on GIS interoperability open platform [3]

Modeling as a process carries some risk of oversimplification of particular situation. All the elements and influences cannot be introduced into the model, for this reason it is necessary to decide which data will be implemented into the model and which will be neglected or simplified [4].

For the understanding of the different views in the software it is required to join a specific number of variables. For flood modelling are key inputs the correctly defined flooding area with location of real occurrence of floods or flood wave course. The most effective way is to use hydrodynamic models which enable modeling of flooding area by integrated 1D/2D models, which we will use for the specific visualization. Basement of modeling is in the link of 1D river model with a 2D model of the built-up area [5]. For this type of mapping and modeling is the most appropriate to use a hydrodynamic model HEC RAS (1D) in combination with software ArcGIS or HEC GeoRAS (2D), that work in GIS environment.

2 Materials and methods

Express the movement of the fluid is not practical. A more suitable method is that the flowing liquid is considered as a continuous environment and each point in the environment has assigned the velocity vector, $v = v(r, t)$. According to this the fluid flow can be divided into hydrostatic ($v = 0$) and hydrodynamic ($v \neq 0$) [6]. Features describing the movement and fluid flow, which were derived from the elemental liquid volume, we can express through;

- law of mass conservation – continuity equation,
- law of momentum conservation,
- law of energy conservation,
- law of entropy change.

Fluid motion can be generally defined as an unsteady and three-dimensional. The task of hydrodynamic is to determine the distribution of the velocity of the flow and determine the pressure in the area of interest. Results can be presented through physical and mathematical modeling. More preferably is the use of mathematical modeling, as physical research is usually more complex because of the financial and time perspective.

Water flow in the open channels is [7] steady or unsteady – where the flow rate (Q), average cross sectional velocity (v) and depth (y) are directly dependent on linear coordinates (x) and time(t).

$$Q=Q(x,t) \qquad v=v(x,t) \qquad y=y(x,t) \tag{1}$$

2.1 Data acquisition for hydraulic model

There are a lot of possibilities and different methods for data acquisition in the practice. The basic ones for data collection are direct and indirect methods [8]:

- geometric methods – tachymetry, leveling, GPS;
- photogrammetric methods
- laser altimetry – airborne laser scanner

Geometric methods of direct measurement represent mainly electronic tachymetry that enables direct electronic recording of polar coordinates or recording of rectangular coordinates, calculated directly on the magnetic card with an accuracy of up to 1 cm. Photogrammetric methods rank among the indirect methods that in short time of its development changed from analog through analytical methods to digital mapping systems. These methods allow horizontal, but also vertical measurements of either mountainous or flat terrain, fixing their geometric properties and spatial situation of photographic images. The accuracy of the special position depends mainly on imaging parameters and ranges from 0.05 m to several meters.

Development of DTM model by laser altimetry allows penetrating through vegetation and trees. That is the main advantage of this method and difference from photogrammetry. This makes it possible to capture the reflection of the laser ray directly from the surface with accuracy less than 0,01m [9]. The most advanced technology for scanning the surface is LIDAR (Light Detection and Ranging), which presents optical remote sensing technology. The principle is the distance between the LIDAR and the scanned object and the output can be exported to BIM software [10].

2.2 Methodology for mathematical modeling

In the 1D models can be expressed different velocity in flow profile trough empirical equations and thus determinate the relative position of the water level in its individual sections. However these values are only approximate and to obtain more precise information is necessary to use multidimensional model. 2D models provide information about the surface division of velocity and depth of the whole territory. Generally, steady flow solution can be identified as less demanding in comparison with the solution of unsteady flow, but when we are dealing with the solution of unsteady flow the transformation of the flood wave and flooded area can be omitted, which can cause in individual cases a large distortion of results and substantial material and financial losses after the implementation of the project. Modelling can be divided into three parts:

- preprocessing – preparation and entering the necessary inputs to the model, import GIS data and define the model output;
- processing – calculation, usually 1D;
- post-processing – process and export of the model outputs for the further processing.

Results from the flow modelling are of great importance for the field of science and practice that their interests are oriented to the construction of waterways, navigation, watercourse regulations and energy – hydro power plants [7].

In mathematical modeling of flow in the river it is necessary to adopt certain assumptions, where is applicable general process solution. A full description of the model is in fact impossible. The first part of the modelling is focused on model development and the second part is application of the model in the practice. The process is divided into several stages of implementation, which can be formulated as follows:

- consider only decisive properties and simplify description of the modeled 3D environment to the flow of water displayed as 1D and flow characteristics represented in 2D;
- determine the choice of a suitable description of the numerical solution;
- discretize the physical area (divided into smaller elements);
- create schematic model of the area as substitute computer network based on finite difference or final elements;
- create general numerical model;
- verify the model based on the already solved models;
- prepare a model for the specific area of interest;
- calibrate the model based on necessary number of control measurements;
- apply verified model for the desire event known as scenarios of calculation.

The whole algorithm shown in the individual stages can generally be divided into two separate parts. The first part focuses on the model development and the second part focuses on the individual characteristics and application of the model in practice [7].

2.3 1D mathematical model HEC-RAS

Within 1D modeling of water flow, the calculation includes a description of the watercourse in the direction of flow with defined cross and valley profiles in the area. It means that in the 1D modeling the spatial location is shown as a distance of respective profiles with dimensions of the banks and bottom. By joining the data from different cross sections is formed the longitudinal profile of the watercourse. We chose 1D model HEC RAS for processing and simulation of the results. Figure 2 shows output from 1D model – the river bed modelled in HEC RAS (modelled Stuliansky creek in eastern Slovakia). From the results it is possible to determine the maximum water level in each profile, the extent of flooding, flow rate, or flow velocity in a particular profile, respecting the changing of the Manning roughness coefficient in each profile.

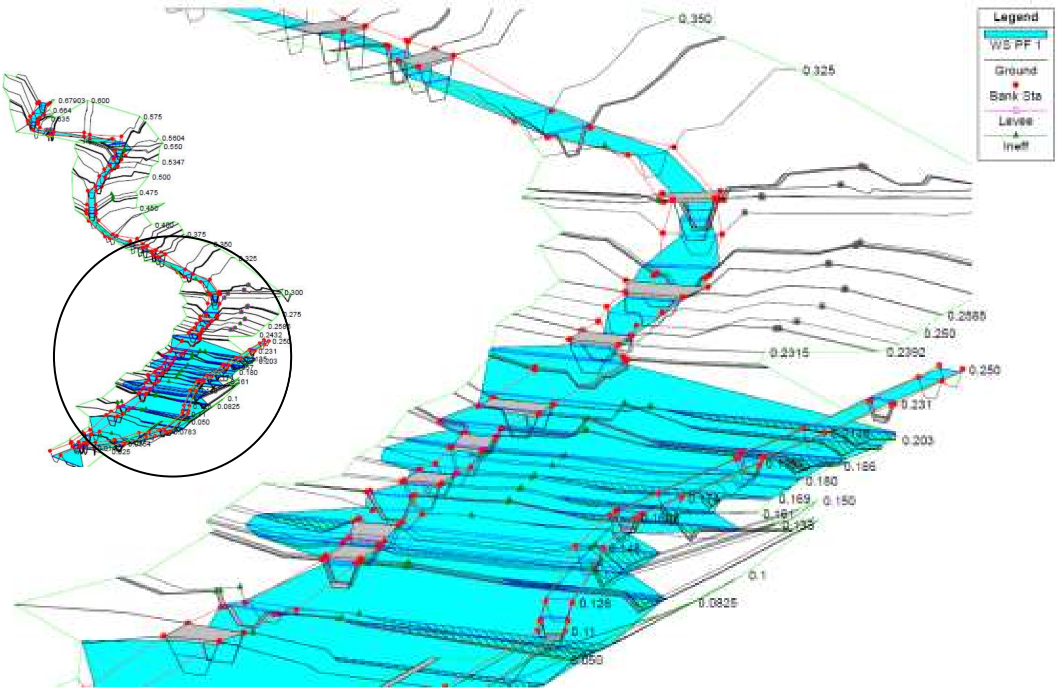

Figure 2: 1D model of Stuliansky stream from HEC-RAS Q_{20}, n = 0.033 in HEC-RAS [13].

Hydrologic Engineering Centers River Analysis System (HEC RAS) [12] is software designed to retrieve data from river system analysis and display them in an interactive network environment. The system includes four one-dimensional hydraulic analysis components:

- Steady Flow Water Surface Profiles;
- Unsteady Flow Simulation;
- Movable Boundary Computations;
- Water Quality Analysis.

A key element is that all four components are used in common hydraulic calculations [11].

HEC RAS software was used in the paper for the modelling of the flooding area in Lopuchov village in eastern Slovakia. In the next chapter the study area and proposal of stream regulation for the purposes of flood protection in the village are described. Detailed procedure of flood modelling in Lopuchov village in eastern Slovakia, what is the core of this paper, is explained in the thesis published by Fijko, 2015 [13].

2.4 Cost benefit analysis

Cost benefit analysis (CBA) involves adding up the benefits of a course of action, and then comparing these with the costs associated with it. Cost benefit analysis is probably the most comprehensive method of economic evaluation available and it can be applied in two approaches. The human capital approach means that the value of people's contributions is linked to what they are paid. The approach based on individuals' observed or stated preference means that their personal valuations are placed on an activity by assessing how much money they are prepared to accept for an increased risk or to pay for a particular service [14].

3 Flood Protection of Lopuchov village

Within the proposed activity **„Preventive Flood Protection Measures – Water streams regulation in village Lopuchov"**, was designed regulation of Stuliansky creek and its left tributary, which is without the name. The developed proposal include the solution of the bottom reconstruction and banks fortification in total length of 672 m of Stuliansky creek (beginning of regulation (BR) in km 0.000 = rkm 4.180; end of regulation (ER) km 0.672 = rkm 4.852) (Figure 3) and its tributary without name in length of 441 m.

Figure 3: Current status of Stuliansky creek (BR=0.000; ER=0.672) Source: Fijko, R (2013).

The aim was to regulate the river profile, so that the river bed has capacity for designed flow of Q_{100} = 24.0 m^3/s (according to Slovak Hydrometeorological Institute). There are no special requirements for the planning construction, either in terms of urban and architectural, although the construction as a whole should not disturb the character of the landscape and should meet the requirements of sustainable development. The construction site is defined by build-up area of the village. Lopuchov village lies in the southwestern part of Nizke Beskydy Mountains in the valley of Stuliansky creek at an average altitude of 223 meters above sea level. Village belongs to the administration of Presov region and is incorporated into the Bardejov district [15].

3.1 Alternatives of design – water stream regulation

Alternative 1: Banks fortification by precast vegetated reinforced concrete blocks with a coefficient of roughness n = 0.033 placed at treated ground, with filling the space for rooting during the construction by green turf;
Alternative 2: Banks fortification by stone tiles placed at the cement mortar, pouring joints with cement mortar, with a coefficient of roughness n = 0.02.
Proposed alternatives were confronted with the unregulated (natural) riverbed with a coefficient of roughness n = 0.07 (Alternative 0).
Alternative 0: The river bed will not be regulated and river banks will not be fortificated – current state, coefficient of roughness n = 0.07.

The main purpose of the work is to propose the protection of the inhabitants and property in the Lopuchov village from flooding by increasing the degree of flood protection [15]. The results from flood modelling using HEC-RAS are used for cost benefit analysis for proposed alternatives of construction.

3.2 Application of mathematical model in GIS

We used the geometric plan of the village in .dwg form to create the model of the area for flood modelling. The model of Stuliansky creek with its tributary was created in HEC RAS, also with defined bridge structures along its course. Figure 4 shows a longitudinal profile of Stuliansky creek with an average inclination of 29.73 ‰. The catchment of Stuliansky creek in village Lopuchov is regularly flooded, which significantly nuisance local residents.

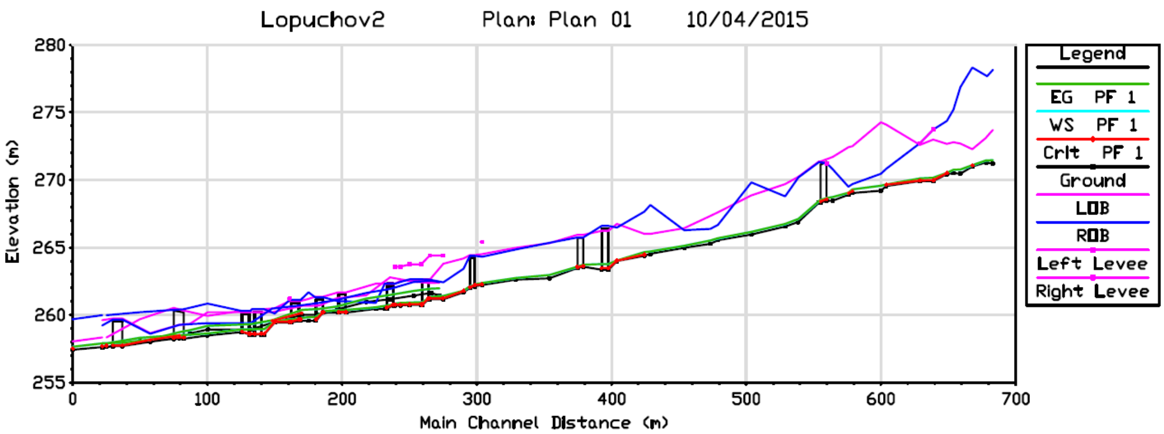

Figure 4: The longitudinal profile of Stuliansky creek, output from HEC RAS

The study area is in terms of geology unstable and is included in the flysch zone. The flooded area can be simulated using 1D mathematical model HEC RAS. We can be read the height of water level or the velocity of flow in the cross profile by the defined discharge. The model of the flooded area for Stuliansky creek, unregulated, with Manning coefficient of 0.07 is presented in Figure 5 for different values of designated discharge – Q_{20}, Q_{50} and Q_{100} and natural flow and in Figure 6 present results regulated flow Q_{100} for alternative 1 and 2.

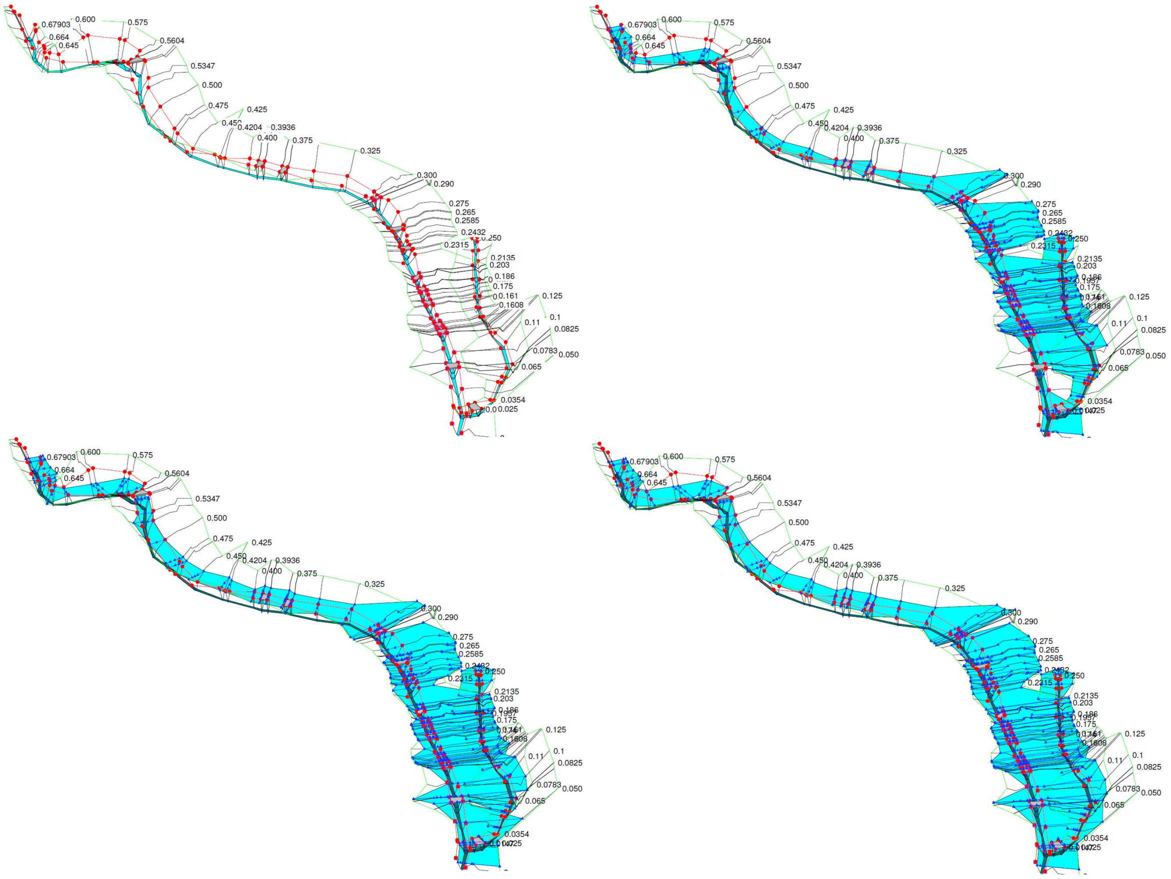

Figure 5: The results of the calculation model HEC-RAS - Alternative 0, Q_1, Q_{20}, Q_{50}, Q_{100}

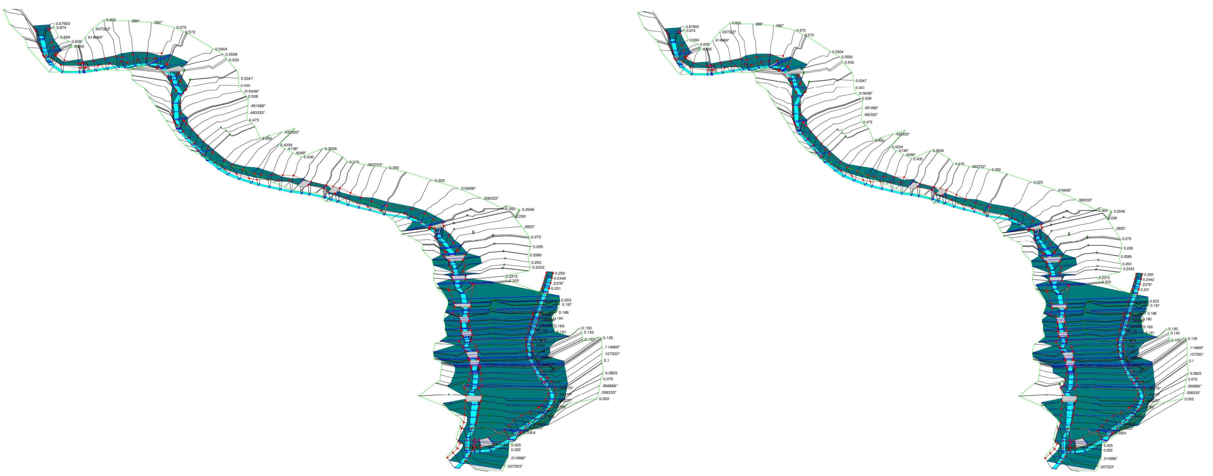

Figure 6: The results of the calculation model HEC-RAS - Alternative 1, Q_{100} (left); Alternative 2, Q_{100} (right)

We modeled three variants of different discharges – Q_1, Q_{20}, Q_{50} and Q_{100} for each of Alternative (Alternative 0, Alternative 1 and Alternative 2).

All the developed models were transferred in the GIS environment, exactly ArcGIS 10.2, where the models were changed from 1D to 3D. In ArcGIS 10.2 was possible to calculate the flooded area for different variants of Alternatives – totally 12 models [13]. Figure 7 display the flooded area of Lopuchov village for daily discharge and designated flow - Q_{100}, for natural, not regulated riverbed.

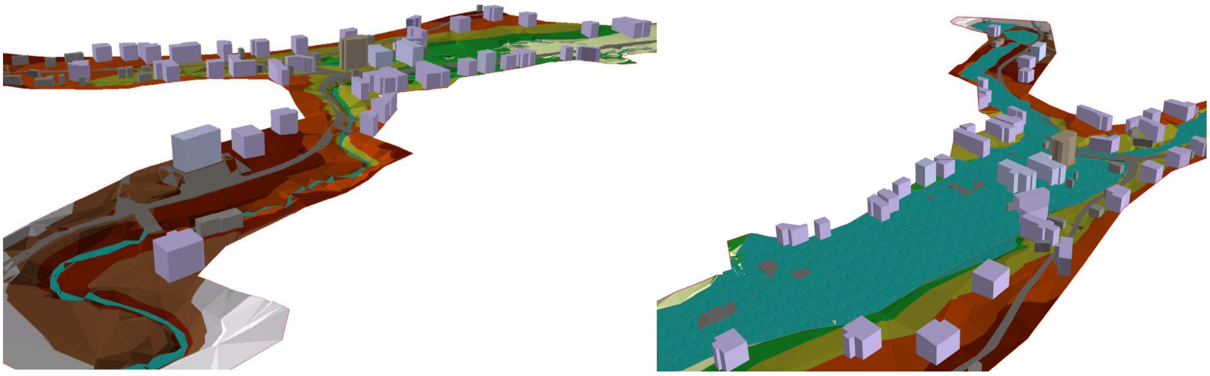

Figure 7: Alternative 0 - display inundation of natural riverbed $Q_1 = 0.04$ m^3/s, $n = 0.07$ and $Q_{100} = 24$ m^3/s, $n = 0.07$

We can conclude from the achieved results that the least flooded area is by Alternative 2 – river banks fortification by stone tiles placed at the cement mortar.

4 Conclusion

Water Framework Directive 2000/60/EC (WFD), Annex III [16], contains a request to develop cost-effective measures. The economic analysis shall contain enough information in order to make judgments about the most cost-effective combination of measures based on estimates of the potential costs of such measures. Because of this requirement it is expected to prepare a cost benefit analysis (CBA). It can significantly help in defining the most appropriate measures, describing the broader social impact of proposed measures. The CBA (Cost Benefit Analysis) to verify that cost incurred on the measures concerned are not greater than monetize benefits that implementation of the measure will bring and whether as a result of proposed measures raise some public benefits [17][17].

Evaluation of flood protection measures consists of determining the size of flooded area, as well as constructions and infrastructure of the urban area. From the flooded area by river discharge $Q_{100,}$ were identified the potential damages and then the costs of damages were compared with the costs of river regulation in both variants (Figure 8). The damage caused by such adjustment should be less than the costs of stream regulation and banks fortification, including possible damage caused by flooding of the study area.

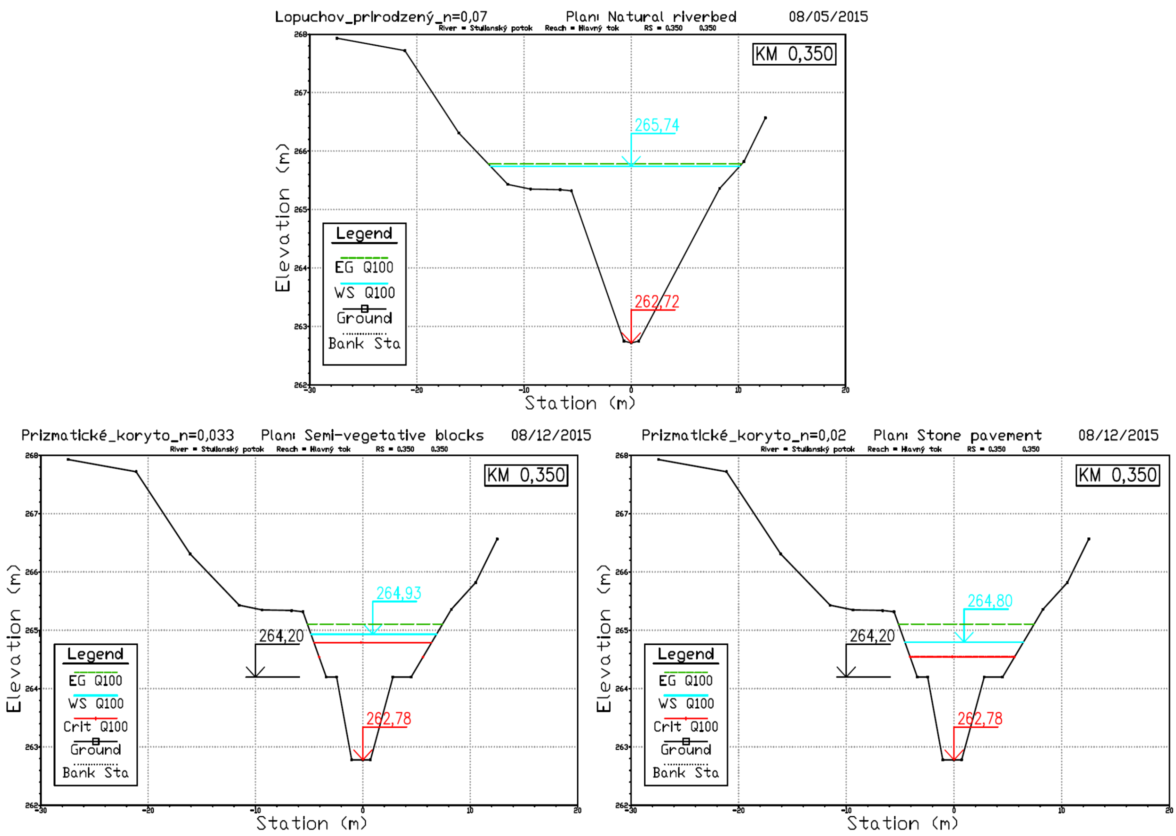

Figure 8: Example of cross section Q_{100} = 24 m^3/s, with Manning coefficients n=0.07, n=0.03 and n=0.02

In the Figure 8 are presented results of maximum water level for separate alternatives of water stream regulations. “EG” shows Energy Grade elevation at downstream end of bridge or culvert, “WS” shows Water Surface elevation upstream of a bridge or culvert and “Crit” is Critical water surface elevation. Water surface is corresponding to the maximum energy and the energy versus depth curve.

Unit cost of damaged property was calculated to be 100 €/m^2 for roads and 525 €/m^2 for building structure. The values were stated from UNIKA 2012 (Collection of indicators of average budget value per measured unit for object. Buildings and constructions according the structure classification.), where the recommended minimum and maximum prices of engineering activities are determined. We calculated the construction budget of water stream regulation in software CENKROS Plus. Items in calculation list (budget) were divided to ground works, foundations, building structures, mass transfer.

There are costs of potential flood damaged in the area if the water stream is not regulated as well as the potential flood damages after water stream regulation. The costs of stream regulation with river banks fortification are also presented in Table 1.

Table 1: Costs of flood damages and flood protection measures at Stuliansky stream

Flow regime	Roughness	Potential damages Σ [€]	Cost of stream regulation without VAT [€]	Cost of stream regulation with VAT [€]	Total cost (damages + regulation) without VAT [€]	Total cost (damages + regulation) with VAT [€]
Natural riverbed	**Without regulation *n*=0.07**	977,735.00				
Regulated stream	**Semi-vegetative blocks *n*=0.033**	408,777.00	284,187.22	341,024.66	692,964.22	749,801.66
	Stone pavement *n*=0.02	238,640.00	394,266.76	473,120.11	632,906.76	711,760.11

It follows that the costs are the most suitable at Alternative 2 – stone tiles placed at the cement mortar with the price of 394,266.76 € without VAT (value added tax) for construction. The designed water discharge 24 m^3/s will be controlled along the village and in comparison with the natural riverbed the flooded areas will be significantly reduced – up to 60%. However, it is impossible to prevent flooding completely, and damage caused of 238,640.00 € amount is about 25% of a total damages estimated at 977,735.00 € by the stream without regulation. Considering the stream regulation with stone tiles used for the banks fortification the flood damages will be reduced by 265,974.89 €, comparing the potential flood damages without regulation.

Inundation area of the village Lopuchov is quite extensive and regulation of water stream in the study area is necessary. Creating of the hydrodynamic model will help in decision making of the selection of suitable flood mitigation measures in term of cost-effectiveness. 1D mathematical model created in HEC-RAS is appropriate way for the designer of the proposed changes, but operates on the principle of calligraphic and insufficiently presents the results to general public. It is therefore appropriate to present the results using a 3D visual representation of what is a better option for potential investors. We used 2D and 3D modelling in software ArcGIS. Correct details of the model will affect the quality of results, but also the speed, numerical calculations and the cost-effectiveness of modeling work.

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References

[1] M-arch architects. (2013, August). *BIM Execution Plans.* Retrieved January 3, 2015, from http://marcharch.com/bim-execution-plans/

[2] Calvert, N. (2013, December). *Why WE care about BIM.* Retrieved January 7, 2015, from http://www.directionsmag.com/entry/why-we-care-about-bim/368436>

[3] Camarinha, R. (2015, November). *Building for the future: BIM and GIS.* Retrieved January 28, 2016, from https://thebimhub.com/2015/11/25/building-for-the-future-bim-gis/#.VqoyxyrhCM9

[4] Hazlinger, M. (2008). Použitie modelu HEC-RAS při modelovaní povodňovej hrozby v povodí Stupávky. In Revelling in Reference: 15 years in geoinformatics - GIS Ostrava, 27-30 January 2008 (pp. 1-12). Ostrava, Czech Republic: VŠB-TU Ostrava.

[5] Kučera, M. & Mišík, M. (2006). Dvojrozmerné modelovanie a povodňové mapovanie. In Revelling in Reference: Flood protection, Proceedings of the International Conference, Podbanské - High Tatras, 4-7 December 2006 (pp. 1-8). High Tatras, Slovakia: RETRO PRINT. ISBN 80-89062-48-2.

[6] Červeň, I. (2014). *E – fyzika*. Textbooks STU Bratislava. Retrieved December 29, 2015, from http://kf-lin.elf.stuba.sk/~ballo/STU_online/e-fyzika-autori%20a%20obsah.htm

[7] Květon, R. (2012). *Matematické modelovanie prúdenia vody v otvorených korytách*. Bratislava: Slovenská technická univerzita v Bratislave. ISBN 978-80-227-3810-1.

[8] Čerňanský, J. & Krcho J. (1999). *Hodnotenie ekotoxikologických faktorov v SR, ich minimalizácia a modelovanie v environmentálnom geoinformačnom systéme.* Bratislava: PRIF UK.

[9] Čerňanský, J. & Kožuch, M. (2014, December). *Metódy priameho geodetického zberu priestorových údajov o terrene.* Retrieved December 28, 2014, from http://www.pce.sk/clanky/body_metody.htm

[10] Schuckman, K. & Renslow, M. (2014). *Introduction to Lasers and LIDAR.* Retrieved November 16, 2014, from https://www.e-education.psu.edu/geog481/l1_p3.html

[11] Hydrologic Engineering Center. (2015). *HEC-RAS River Analysis System, Hydraulic Reference Manual. Version 1.0*. Institute for Water Resources: Washington DC. Retrieved January 22, 2016, from http://www.hec.usace.army.mil/software/hec-ras/documentation.aspx

[12] U.S. Army Corps of Engineers. (2014). HEC-RAS River Analysis System. [HEC-RAS 4.1]. Institute for Water Resources: Washington DC.

[13] Fijko, R. (2015). *Využitie BIM technológií pre úpravy vodných tokov.* Published diploma thesis, Technical University of Košice, Košice, Slovakia.

[14] Robinson, R. (1993, October). Economic Evaluation and Health Care, Cost Benefit Analysis. *The BMJ*. 307 (6919), 924-926. Retrieved January 22, 2016, from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1679054/pdf/bmj00042-0048.pdf

[15] Zeleňáková, M., Sarka, D. & Zvijáková, L. (2011). *Preventívne protipovodňové opatrenia - Úprava vodných tokov v obci Lopúchov*. Košice, Technical University of Košice, Košice, Slovakia.

[16] Ministry of the Environment, Department of Water Protection. (2001). *Directive 2000/60 / EC of the European Parliament and of the Council.* Prague: Ministry of the Environment.

[17] Drdulová, E. (2007). *Metodika na hodnotenie efektívnosti nákladov.* WRI Bratislava. Retrieved May, 2, 2015, from: http://www.vuvh.sk/rsv2/download/02_Dokumenty/10_Podpone_dokumenty_metodiky/17_Metodika_CEA_2007_SK.pdf